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GLOBAL UNCERTAINTY ANALYSIS OF FULL-SCALE SUBMARINE PROPULSION PREDICTIONS USING MODEL TESTS IN THE LCC

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ABSTRACT

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INTRODUCTION

Estimates of the uncertainties attached to full-scale predictions of submarine propulsion based on propulsion tests in the LCC are obtained in this study by means of a global uncertainty analysis. The analysis takes into account the uncertainties associated with the prediction procedure and the measurements performed both at model scale and at full scale. Thus, the uncertainty analysis developed in the study takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

The prediction procedure, summarized in Appendix A, entails both tow-tank resistance tests to determine the residuary-drag coefficient, and propulsion tests in the LCC. Five primary model-scale variables are measured in LCC propulsion tests. These measured primary model-scale variables are the reference velocity, the drag, and the propeller rpm, thrust and torque.

The five measured primary model-scale variables are used to determine several "transformed" model-scale variables by means of analytical relations. These relations are given in Appendix A. The transformed model-scale variables include

four nondimensional variables : the total-drag coefficient, the advance ratio, the thrust-deduction factor, and the propulsive efficiency.

The curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are fundamental elements of the model-scale to full-scale extrapolation. The relations used in this extrapolation are given in Appendix A. The extrapolation procedure is usually implemented for a specified full-scale speed or for a specified full-scale shaft horsepower. Both cases are examined in the global uncertainty analysis developed in the study.

The uncertainty analysis, based on classical expressions for the errors [1] and elementary differential calculus, is expounded in Appendix B. The Fortran-code implementation of the expressions for the uncertainties obtained in Appendix B is given in Appendix C. Example input and output files associated with the Fortran-code are also included in Appendix C. The global uncertainty analysis developed in Appendices B and C provides a practical tool for estimating the uncertainties of full-scale predictions in terms of component uncertainties attached to model-scale and full-scale measurements.

Full-scale theoretical predictions are ultimately compared to values measured in full-scale trials. The observed differences between theoretical predictions obtained via model-scale tests and full-scale measurements are usually expressed in the form of a correlation allowance in the relation defining the drag coefficient.

The correlation allowance accounts for aspects of the full-scale flow, such as the hull roughness, that are not accounted for in model tests. The correlation allowance also accounts for other limitations of the procedure used to obtain full-scale predictions from model tests, notably errors that are systematically introduced into the predictions as a result of limitations inherent to the prediction procedure. Thus, systematic errors associated with the characteristics of the LCC and of the experimental set-up used in the implementation of the procedure are largely included in the correlation allowance, as is attested by the fact that different

correlation allowances are used for different facilities such as the LCC and tow tanks.

Thus, the correlation allowance largely accounts for the systematic (bias) errors associated with the effects of the walls of the test section of the LCC, the strut holding the model, the strain gauges, and the electronic equipment. Therefore, as long as no significant changes are made in the characteristics of the LCC, the experimental set-up (including the strut, the strain gauges, and the electronic equipment) and the testing procedure, systematic errors attached to these aspects of the prediction procedure can largely be ignored in the uncertainty analysis (since they are already included in the correlation allowance to a large extent, as was noted previously).

Some errors, however, are likely to vary with the design speed, and thus cannot be completely ignored in the uncertainty analysis. Systematic errors due to geometrical imprecisions of the model clearly are model-dependent, and thus cannot in principle be ignored in the uncertainty analysis.

In summary, it is appropriate to ignore most systematic (bias) errors in an uncertainty analysis of a consistent prediction procedure because these consistent errors are largely included in the correlation allowance attached to the prediction procedure. This general consideration and consideration of the substantial difficulties in obtaining realiable estimates of bias errors --- more precisely, of the effects of the bias errors that are not already included in the correlation allowance --- suggest that a reasonable practical way of accounting for bias errors is to simply increase the precision (random) errors by means of a multiplicative factor. Specifically, the bias errors of the measured primary model-scale variables are taken equal to the precision errors of these variables in the analysis considered further on.

The precision errors attached to the measured primary model-scale variables can be determined by means of a statistical analysis of the repeatability of model-scale measurements. This repeatability analysis is presented in Appendix D.

Results of the repeatability analysis presented in Appendix D and of the global uncertainty analysis expounded in Appendix B are presented below for several cases, with the purpose of analyzing the contribution of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

RESULTS OF UNCERTAINTY ANALYSIS

The uncertainty analysis developed in this study is applied to a typical case, which is defined below (and in the input file listed in Appendix C). The identifying numbers of the model, the propeller, and the resistance (EHP) and propulsion (SHP) tests corresponding to the case considered here are

model no.	propeller no.	EHP exp. no.	SHP exp. no.
XXXX	XXXX	XXX	XXX

The water density and viscosity are

density	viscosity
1.937 $slug/ft^3$	$1.084 X 10^{-5}$ ft^2/sec

The length and the wetted area of the model, and the diameter of the propeller are

length	area	diameter
22.697 ft	138.179 ft^2	0.9986 ft

The residuary-drag coefficient, determined via tow-tank resistance (EHP) model-tests, is taken as

residuary-drag coefficient
0.00065

The reference velocity, the propeller rpm, the total drag R_T, the tow force ΔR, and the propeller thrust and torque in the propulsion tests are

ref. velocity	rpm	drag	tow force	thrust	torque
23.7 knots	1175.0	717.89 lbs	191.10 lbs	878.0 lbs	2585.0 in-lbs

The slopes of the curves representing the advance ratio, the thrust-deduction factor, and the propulsive efficiency as functions of the total-drag coefficient are equal to

advance ratio	thrust-deduction factor	propulsive efficiency
-0.249	0.067	-0.015

The length and the speed of the full-scale submarine are

length	speed
380 ft	25 knots

Finally, the viscosity of sea water is taken as 1.282×10^{-5} ft^2/sec.

As was already noted, results of the repeatability analysis presented in Appendix D and the global uncertainty analysis expounded in Appendices B and C are presented for several cases for the purpose of analyzing the contributions of the major component uncertainties which influence the overall uncertainty of full-scale predictions.

Case M1 : contribution of precision-uncertainties of model-scale measurements

It is instructive to first consider the full-scale prediction-uncertainties for the case when only the uncertainties stemming from propulsion tests in the LCC are taken into account. In this case, called M1 hereafter, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are presumed known without uncertainty. The residuary-drag coefficient (determined via tow-tank resistance tests), the density and the viscosity of the water in the LCC, the length and the wetted area of the model, and the propeller diameter are also presumed known without uncertainty for case M1. Furthermore, model-scale uncertainties are taken

equal to the precision (random) errors determined in Appendix D. Thus, bias errors attached to the measured primary model-scale variables are not taken into account in case M1. Case M1 corresponds to a comparison of successive model-tests within a series of consecutive tests.

Appendix D indicates that the relative precision uncertainties in propulsion tests are approximately equal to 1% for the reference velocity, 0.2% for the propeller rpm, 1.5% for the drag R_T and the tow force ΔR, 0.5% for the propeller thrust and 0.3% for the propeller torque. These uncertainties are listed below :

Precision uncertainties of model-scale measurements in propulsion tests

velocity	rpm	drag & tow force	thrust	torque
1%	0.2%	1.5%	0.5%	0.3%

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP.

Full-scale prediction-uncertainties for case M1

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	1.0%	2.15%	2.6%	2.35%	0.0%
SHP	0.8%	1.3%	2.65%	1.3%	n/a	2.35%

The prediction-uncertainties listed in the foregoing table represent the contribution of precision errors of measurements in the LCC when all other sources of errors (including bias errors of model-scale measurements, uncertainties of the residuary-drag coefficient determined via tow-tank resistance tests, uncertainties of the density and the viscosity of the water in the LCC, and model-scale geometrical inaccuracies) are ignored.

The contribution of the uncertainties attached to the residuary-drag coefficient determined from tow-tank resistance tests, the density and the viscosity of the water in the LCC, the model length and wetted area, and the propeller diameter, are considered in case M2, and the sensitivity of prediction-uncertainties attached to model-scale bias errors is considered in case M3.

Case M2 : contribution of uncertainties attached to water properties, model-scale geometry, and residuary-drag coefficient

The uncertainties of the density and the viscosity of the water in the LCC, the model length and area, and the propeller diameter are taken as is indicated in the following table :

Uncertainties of water properties and model-scale geometry

density	viscosity	length	area	diameter
0.1%	1.5%	0.1%	0.5%	0.05%

A global uncertainty analysis of full-scale resistance and propulsion using tow-tank model tests [2] shows that the uncertainty of the residuary-drag coefficient is approximately 8.6% , i.e.

uncertainty of residuary-drag coefficient
9%

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the uncertainties of model-scale measurements defined in case M1 and the uncertainties of the residuary-drag coefficient, LCC-water properties and model-scale geometry now considered are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP, as for case M1.

Full-scale prediction-uncertainties for case M2

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	1.0%	3.2%	3.5%	3.35%	2.35%
SHP	1.15%	1.55%	2.8%	1.55%	n/a	2.35%

The increase in uncertainties from case M1 to case M2 are mainly due to the incertainty of the residuary-drag coefficient. In fact, it can be verified that the uncertainties of the density and the viscosity of water in the LCC, of the length and the wetted area of the model, and of the diameter of the propeller are sufficiently small that they have insignificant effect upon the prediction-uncertainties.

Case M3 : contribution of model-scale precision and bias uncertainties

As in cases M1 and M2, only the contribution of model-scale uncertainties are considered in case M3. Thus, the correlation allowance and full-scale conditions (i.e. the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, the full-scale values of the speed, the propeller rpm, the thrust, the torque, and the shaft horsepower) are again presumed known without uncertainty for the case now considered.

As was already noted in the introduction, model-scale bias errors are taken equal to the model-scale precision errors determined in Appendix D and listed previously for cases M1 and M2. The total (precision + bias) model-scale uncertainties which are considered in case M3 are then equal to $2^{1/2}$ times the model-scale uncertainties considered in cases M1 and M2 . Thus, the uncertainty of the residuary-drag coefficient is now taken as 8.6% X $2^{1/2}$ = 12.2% , i.e.

uncertainty of residuary-drag coefficient
12%

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the previously-defined model-scale uncertainties are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP, as for cases M1 and M2. This table shows that the prediction-uncertainties for case M3 are approximately equal to $2^{1/2}$ times the prediction-uncertainties for case M2, as one expects.

Full-scale prediction-uncertainties for case M3

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	n/a	1.45%	4.35%	4.8%	4.55%	3.15%
SHP	1.55%	2.1%	3.9%	2.1%	n/a	3.3%

The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using submarine model testing in the LCC for a specified full-scale submarine and propeller geometry and specified full-scale conditions. However, comparisons of full-scale predictions obtained by means of model testing to measurements in full-scale trials introduce additional uncertainties. These additional uncertainties, called full-scale uncertainties hereafter, stem from uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is determined in case F.

Case F : contribution of full-scale uncertainties

All model-scale uncertainties are ignored in case F, which only considers the contribution of full-scale uncertainties. Thus, all model-scale variables and the correlation allowance are presumed known without uncertainty in case F.

The relative uncertainties of the density and the viscosity of sea water, of the length and the wetted-surface area of the full-scale submarine, and of the propeller diameter are taken as is indicated in the following table :

Uncertainties of full-scale input variables

density	viscosity	length	area	diameter
1%	2%	0.5%	1%	0.1%

The uncertainties of full-scale measurements are considered in Appendix E . The total (precision + bias) uncertainties of full-scale measurements are taken as

Uncertainties of full-scale measurements

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

hereafter.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP associated with the foregoing full-scale uncertainties are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP.

Full-scale prediction-uncertainties for case F

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	0.75%	3.5%	2.05%	2.45%	2.25%
SHP	0.85%	0.7%	3.1%	1.2%	0.9%	0.9%

The prediction-uncertainties for case F, which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored), are smaller than the prediction-uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

Case MF : contribution of model-scale and full-scale uncertainties

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F, respectively, are now combined. The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called case MF hereafter, are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP.

Full-scale prediction-uncertainties for case MF

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	1.6%	5.6%	5.2%	5.15%	3.85%
SHP	1.75%	2.25%	5.0%	2.4%	0.9%	3.45%

The uncertainties for case MF are larger than the uncertainties for either case M3 or case F, as one expects.

Case MFC : sensitivity to variations in the correlation allowance

The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty. However, variations in the values of the correlation allowance occur, due to variations in the full-scale submarine that are not accounted for in model tests (e.g. variations in the hull roughness) as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced at

model scale and full scale are largely, but not fully, included in the correlation allowance.

The correlation allowance is taken equal to 0.00035 for the typical case examined in the present uncertainty analysis. Experience with tow-tank propulsion predictions for the SSN 688 class submarine indicates variations of the correlation allowance within a fairly broad range. Inasmuch as the contributions of model-scale uncertainties and full-scale uncertainties are already included in the full-scale prediction-uncertainties obtained in case MF, a variation of the correlation allowance approximately equal to 30% is considered here. Specifically, variations of the correlation allowance within the range

$$CA = 0.00035 +/-0.0001$$

are considered in case MFC. Thus, the prediction-uncertainties obtained when the effect of a 30% variation in the value of the correlation allowance is added to the model-scale and full-scale uncertainties considered in case MF is examined in case MFC.

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for the full-scale speed, rpm, thrust, torque, SHP and EHP for this case, called case MFC, are listed in the next table for two cases corresponding to predictions for specified values of the full-scale speed or SHP.

Full-scale prediction-uncertainties for case MFC

at given	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP
speed	0.6%	1.6%	6.9%	6.55%	6.55%	5.55%
SHP	2.25%	2.6%	5.15%	2.8%	0.9%	3.45%

CONCLUSION

In summary, a tool for estimating the uncertainties attached to full-scale predictions of submarine propulsion using model tests in the LCC has been developed, by means of a global uncertainty analysis, and applied to a typical case. The analysis takes into account the uncertainties associated with the prediction procedure and the uncertainties of measurements performed both at model scale and at full scale. Thus, the analysis developed and applied here takes into account all the component uncertainties which influence the overall uncertainty of full-scale predictions.

Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP attached to the full-scale speed, rpm, thrust, torque, SHP and EHP have been obtained for two cases, corresponding to predictions for specified values of the full-scale speed or SHP . Estimates of the prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP are given for six cases, called M1, M2, M3, F, MF and MFC.

The prediction-uncertainties for case M1 represent the contribution of precision errors of model-scale measurements in the LCC when all other sources of errors (including bias errors of model-scale measurements, uncertainty of the residuary-drag coefficient, uncertainties of the density and the viscosity of the water in the LCC, and model-scale geometrical inaccuracies) are ignored. Thus, bias errors attached to the primary model-scale variables measured in the LCC are not taken into account in M1, which corresponds to successive model tests within a series of consecutive tests.

The contribution of uncertainties of the residuary-drag coefficient, the density and the viscosity of the water in the LCC, the model length and wetted area, and the propeller diameter, are considered in case M2 . The increase in uncertainties from case M1 to case M2 are mainly due to the uncertainty of the residuary-drag coefficient. In fact, it can be verified that the uncertainties of the density and the viscosity of water in the LCC, of the length and the wetted area of the model, and of

the diameter of the propeller are sufficiently small that they have insignificant effect.

The sensitivity of prediction-uncertainties to model-scale bias errors is considered in case M3. Model-scale bias errors are taken equal to the model-scale precision (random) errors considered in cases M1 and M2. Thus, the prediction-uncertainties for case M3 are equal to $2^{1/2}$ times the prediction-uncertainties for case M2, as one expects. The prediction-uncertainties for case M3 may be regarded as the uncertainties of the full-scale predictions obtained using submarine model testing in the LCC for a specified full-scale submarine and propeller geometry and specified full-scale conditions.

Comparison of full-scale predictions to measurements in full-scale trials introduces additional uncertainties. These additional full-scale uncertainties stem from uncertainties in the values of the density and the viscosity of sea water, the geometry of the full-scale ship and propeller, and the values of the full-scale speed, propeller rpm, thrust, torque, and shaft horsepower. The contribution of these full-scale uncertainties to the prediction-uncertainties is considered in case F , which only considers the contribution of full-scale uncertainties (with all other sources of uncertainties ignored). The prediction-uncertainties for case F are smaller than the prediction-uncertainties for case M3, which only considers the contribution of model-scale uncertainties (with all other sources of uncertainties ignored).

The contributions of both the model-scale uncertainties and the full-scale uncertainties considered in cases M3 and F , respectively, are combined in case MF . Thus, the uncertainties for case MF are larger than the uncertainties for either case M3 or case F . The prediction-uncertainties for case MF are based on the assumption that the correlation allowance is known without uncertainty.

However, variations in the value of the correlation allowance occur, due to variations in the full-scale submarine that are not accounted for in the model-tests (such as variations in the hull roughness), as well as uncertainties attached to both model-scale and full-scale variables. As is noted in the introduction, bias errors systematically introduced at model scale and full scale are largely, although not

fully, included in the correlation allowance. Inasmuch as the contributions of model-scale and full-scale uncertainties are already included in the full-scale prediction-uncertainties evaluated in case MF, the effect of a 30% variation in the value of the correlation allowance added to the model-scale and full-scale uncertainties considered in case MF is examined in case MFC .

The cases M1, M2, M3, F, MF and MFC are summarized below

Cases M1, M2, M3, F, MF and MFC

M1	only considers precision uncertainties of model-scale measurements
M2	adds uncertainties of residuary-drag coefficient, LCC-water properties and model-scale geometry
M3	considers all model-scale precision and bias uncertainties
F	only considers full-scale uncertainties
MF	considers all model-scale and full-scale uncertainties
MFC	adds sensitivity to variations in correlation allowance

The prediction-uncertainties Uspeed, Urpm, Uthrust, Utorque, USHP and UEHP for a specified value of the full-scale SHP are listed in the following table for the six cases M1, M2, M3, F, MF and MFC. The uncertainty UPC of the propulsive efficiency is also given in the table

Full-scale prediction-uncertainties for a specified SHP

case	Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
M1	0.8%	1.3%	2.65%	1.3%	n/a	2.35%	2.35%
M2	1.15%	1.55%	2.8%	1.55%	n/a	2.35%	2.35%
M3	1.55%	2.1%	3.9%	2.1%	n/a	3.3%	3.3%
F	0.85%	0.7%	3.1%	1.2%	0.9%	0.9%	n/a
MF	1.75%	2.25%	5.0%	2.4%	0.9%	3.45%	3.3%
MFC	2.25%	2.6%	5.15%	2.8%	0.9%	3.45%	3.3%

In summary, it may be concluded that the full-scale prediction-uncertainties for a specified SHP are approximately equal to

Summary of full-scale prediction-uncertainties for a specified SHP

Uspeed	Urpm	Uthrust	Utorque	USHP	UEHP	UPC
2%	2.5%	5%	3%	1%	3.5%	3%

APPENDIX A : PREDICTION PROCEDURE

Primary model-scale variables

Primary model-scale variables are determined from measurements. Five major primary variables are measured : the reference velocity V, the drag R, and the propeller rps n, thrust T and torque Q.

Transformed model-scale variables

Transformed model-scale variables are obtained from the measured primary variables by means of analytical relations. The major transformed model-scale variables are the total-drag coefficient C_T, the advance ratio J_V, the thrust-deduction factor $1-t$ and the propulsive efficiency η_D. The relations defining these transformed variables are given below.

It is assumed here that the LCC is used to perform propulsion tests, but that the resistance (EHP) tests required to determine the residuary-drag coefficient C_R are performed in a tow tank. Thus, the uncertainty attached to the residuary-drag coefficient C_R, determined via tow-tank model tests, is presumed known (i.e., is an input) in the uncertainty analysis considered further on.

The reference velocity V for steady flow past a model held fixed inside the test section of the LCC is determined via Laser Doppler Velocimetry (LDV) measurement of the fluid velocity at a section of the flow where the pressure coefficient C_p vanishes. The location of the $C_p = 0$ reference section is determined using a computational method. Propulsion tests performed in the LCC yield the ideal resistance R_i

$$R_i = R_T - \Delta R \tag{1}$$

where R_T is the drag of the model without propeller and ΔR is the change in the drag due to the propeller. The total-drag coefficient C_T of the model in a propulsion test is given by

$$C_T = \frac{R_i}{\rho S V^2/2} \tag{2}$$

where ρ is the density of the tank water, S is the wetted-surface area of the model, and V is the previously-defined reference velocity. The advance ratio J_V is defined as

$$J_V = V/(nD) \tag{3}$$

where n and D are the propeller *rps* and diameter. The thrust-deduction factor $1-t$ is given by

$$1 - t = R_i / T \tag{4}$$

where T is the propeller thrust. The propulsive efficiency η_D is

$$\eta_D = \frac{V R_i}{2\pi\, n\, Q} \tag{5}$$

where Q is the propeller torque. The three curves representing the nondimensional variables J_V, $1-t$ and η_D as functions of C_T are used to determine full-scale predictions.

Full-scale predictions

The superscript S identifies full-scale variables. No superscript is used for model-scale variable. At a given ship speed V^S, the total-drag coefficient C_T^S, the propeller rps n^S, thrust T^S and torque Q^S, and the shaft horsepower SHP^S are determined using the relations given below.

The friction-drag coefficient C_F^S is determined using the ITTC formula

$$C_F^S = 0.075/(C \ln R_n^S - 2)^2 \tag{6a}$$

where $C \simeq 0.4342944819$. The Reynolds number R_n^S is defined as

$$R_n^S = V^S L^S / \nu^{sea} \tag{6b}$$

where L^S is the ship length and ν^{sea} is the kinematic viscosity of sea water. The total-drag coefficient C_T^S of the ship is evaluated using the relation

$$C_T^S = C_F^S + C_R + C_A \tag{7}$$

where C_F^S is the friction-drag coefficient, C_R is the residuary-drag coefficient determined from resistance (EHP) tow-tank model tests, and the correlation allowance C_A accounts for differences between the actual drag coefficient C_T^S and the predicted drag coefficient $C_F^S + C_R$.

The propeller rps is obtained from the relation

$$n^S = \frac{V^S}{J_V^S D^S} \tag{8}$$

where D^S is the propeller diameter. Furthermore, the advance ratio J_V^S is determined from the function $J_V(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S predicted by (7).

The total drag of the ship R_T^S and the power required to overcome R_T^S are given by

$$R_T^S = C_T^S \rho^{sea} S^S (V^S)^2/2$$

$$EHP^S = R_T^S V^S = C_T^S \rho^{sea} S^S (V^S)^3/2 \tag{9}$$

where ρ^{sea} is the density of sea water and S^S is the wetted-surface area of the ship.

The thrust T^S exerted by the propeller is evaluated using the relation

$$T^S = \frac{R_T^S}{1-t^S} = \frac{C_T^S}{1-t^S} \rho^{sea} S^S (V^S)^2/2 \tag{10}$$

where the thrust-deduction factor $1-t^S$ is determined from the function $(1-t)(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (7).

The power provided to the propeller is

$$SHP^S = \frac{EHP^S}{\eta_D^S} = \frac{C_T^S}{\eta_D^S} \rho^{sea} S^S (V^S)^3/2 \tag{11}$$

where the propulsive efficiency η_D^S is determined from the function $\eta_D(C_T)$ obtained from model tests, with C_T taken equal to the full-scale value C_T^S given by (7).

Finally, the propeller torque Q^S is defined by

$$Q^S = \frac{SHP^S}{2\pi\, n^S} = \frac{C_T^S\, J_V^S D^S}{4\pi\, \eta_D^S}\, \rho^{sea}\, S^S (V^S)^2 \tag{12}$$

where (11) and (8) were used.

The foregoing relations yield values of the shaft horsepower SHP^S corresponding to a range of values of the ship speed V^S. A plot of the speed V^S as a function of the horsepower SHP^S is then used to determine the ship speed V^S corresponding to a prescribed value of the power SHP^S.

APPENDIX B : GLOBAL UNCERTAINTY ANALYSIS

Uncertainties of measured model-scale variables

The previous relations, which define model-scale and full-scale variables in terms of five measured primary model-scale variables (reference velocity V, drag R, and propeller rps n, thrust T and torque Q), can be used to determine the uncertainties of the transformed model-scale variables and of the predicted full-scale variables in terms of the uncertainties of the measured primary variables. These analytical expressions for the uncertainties of the transformed model-scale variables and of the full-scale predictions are given below.

Uncertainties of transformed model-scale variables

Expression (1) yields

$$dR_i = dR_T - d\Delta R$$

The absolute uncertainty of R_i therefore is given by

$$\delta R_i = \sqrt{\left(\frac{\delta R_T}{R_T}\right)^2 (R_T)^2 + \left(\frac{\delta \Delta R}{\Delta R}\right)^2 (\Delta R)^2} \tag{13}$$

Expression (2) yields

$$\frac{dC_T}{C_T} = \frac{dR_i}{R_i} - \frac{d\rho}{\rho} - \frac{dS}{S} - 2\frac{dV}{V}$$

The relative uncertainty of C_T is then given by

$$\left(\frac{\delta C_T}{C_T}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta S}{S}\right)^2 + 4\left(\frac{\delta V}{V}\right)^2 \tag{14}$$

Expression (3) defines the relative uncertainty of the advance ratio J_V as

$$\left(\frac{\delta J_V}{J_V}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta D}{D}\right)^2 \tag{15}$$

The relative uncertainty of the thrust-deduction factor $1-t$ is defined by (4) as

$$\left(\frac{\delta(1-t)}{1-t}\right)^2 = \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta T}{T}\right)^2 \tag{16}$$

The relative uncertainty of the propulsive efficiency η_D is defined by (5) as

$$\left(\frac{\delta \eta_D}{\eta_D}\right)^2 = \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta R_i}{R_i}\right)^2 + \left(\frac{\delta n}{n}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2 \tag{17}$$

In (14) and (16)-(17), δR_i is given by (13).

Uncertainties of full-scale predictions

Expressions (6) yield

$$\frac{dC_F^S}{C_F^S} = \frac{-2\,C}{C\ln R_n^S - 2}\,\frac{dR_n^S}{R_n^S} = \frac{-2\,C}{\sqrt{0.075}}\sqrt{C_F^S}\left(\frac{dV^S}{V^S} + \frac{dL^S}{L^S} - \frac{d\nu^{sea}}{\nu^{sea}}\right)$$

$$= -\sqrt{\widehat{C}\,C_F^S}\left(\frac{dV^S}{V^S} + \frac{dL^S}{L^S} - \frac{d\nu^{sea}}{\nu^{sea}}\right)$$

where $\widehat{C} = 4\,C^2/0.075 \simeq 10.0593$. We thus have

$$\frac{dC_F^S}{C_F^S} = -\sqrt{10\,C_F^S}\left(\frac{dV^S}{V^S} + \frac{dL^S}{L^S} - \frac{d\nu^{sea}}{\nu^{sea}}\right) \tag{18}$$

Expression (7) for the total-drag coefficient C_T^S yields

$$dC_T^S = dC_F^S + dC_R + dC_A$$

which can be expressed in the form

$$\frac{dC_T^S}{C_T^S} = \frac{C_F^S}{C_T^S}\frac{dC_F^S}{C_F^S} + \frac{dC_R + dC_A}{C_T^S}$$

We then have

$$\frac{dC_T^S}{C_T^S} = \Gamma\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \tag{19}$$

where Γ and $D_C^{L\nu}$ are defined as

$$\Gamma = \sqrt{10\,C_F^S}\,\frac{C_F^S}{C_T^S} \tag{20}$$

$$D_C^{L\nu} = \frac{dC_R + dC_A}{\sqrt{10\,C_F^S}\,C_F^S} - \frac{dL^S}{L^S} + \frac{d\nu^{sea}}{\nu^{sea}} \tag{21}$$

Expressions (8), (10), (11) and (12) involve the nondimensional coefficients J_V, $1-t$ and η_D. These coefficients are determined from curve fits (obtained from model tests) of J_V, $1-t$ and η_D as functions of C_T. Let Λ stand for any one of the three coefficients J_V, $1-t$ and η_D. The difference in the coefficient Λ is given by

$$d\Lambda\,|_{C_T^S} + \frac{d\Lambda}{d\,C_T}\,dC_T^S$$

The first term represents the difference in Λ at a given value of C_T^S, and the second term defines the difference in Λ due to the uncertainty of C_T^S. Let the first term be written as $d\Lambda$ for shortness. The relative difference in Λ may then be expressed in the form

$$\frac{d\Lambda}{\Lambda} + \frac{d\Lambda}{d\,C_T}\,\frac{C_T^S}{\Lambda}\,\Gamma\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right)$$

where (19) was used. The relative differences in the coefficients J_V, 1$-t$ and η_D are then given by

$$\frac{dJ_V}{J_V} + \sigma^J\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \qquad \frac{d(1-t)}{1-t} + \sigma^t\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \qquad \frac{d\eta_D}{\eta_D} + \sigma^\eta\left(D_C^{L\nu} - \frac{dV^S}{V^S}\right) \tag{22}$$

where σ^J, σ^t and σ^η are defined as

$$\sigma^J = \sqrt{10\,C_F^S}\,\frac{C_F^S}{J_V}\,\frac{dJ_V}{dC_T} \qquad \sigma^t = \sqrt{10\,C_F^S}\,\frac{C_F^S}{1-t}\,\frac{d(1-t)}{dC_T} \qquad \sigma^\eta = \sqrt{10\,C_F^S}\,\frac{C_F^S}{\eta_D}\,\frac{d\eta_D}{dC_T} \tag{23}$$

Here, expression (20) for the term Γ was used.

It is also useful to define the notation

$$D_V = \frac{dV^S}{V^S} \qquad D_N = \frac{dn^S}{n^S} \qquad D_T = \frac{dT^S}{T^S} \qquad D_Q = \frac{dQ^S}{Q^S} \qquad D_P = \frac{dSHP^S}{SHP^S} \tag{24a}$$

$$D_\rho^S = \frac{d\rho^{sea}}{\rho^{sea}} + \frac{dS^S}{S^S} \qquad D_t = \frac{d(1-t)}{1-t} \qquad D_\eta = \frac{d\eta_D}{\eta_D} \qquad D_J^D = \frac{dJ_V}{J_V} + \frac{dD^S}{D^S} \tag{24b}$$

Expressions (8), (10), (11), (12), (19), (22) and (24) yield

$$D_N = (1+\sigma^J)\,D_V - \sigma^J D_C^{L\nu} - D_J^D \tag{25a}$$

$$D_T = (2-\Gamma+\sigma^t)\,D_V + (\Gamma-\sigma^t)\,D_C^{L\nu} + D_\rho^S - D_t \tag{25b}$$

$$D_Q = (2-\Gamma+\sigma^\eta-\sigma^J)\,D_V + (\Gamma-\sigma^\eta+\sigma^J)\,D_C^{L\nu} + D_\rho^S - D_\eta + D_J^D \tag{25c}$$

$$D_P = (3-\Gamma+\sigma^\eta)\,D_V + (\Gamma-\sigma^\eta)\,D_C^{L\nu} + D_\rho^S - D_\eta \tag{25d}$$

where the relative differences dJ_V^S/J_V^S, $d(1-t^S)/(1-t^S)$ and $d\eta_D^S/\eta_D^S$ have been taken equal to the corresponding model-scale values dJ_V/J_V, $d(1-t)/(1-t)$ and $d\eta_D/\eta_D$.

The four relations (25) involve model-scale variables and differences — which occur via the four terms dC_R/C_R, dJ_V/J_V, $d(1-t)/(1-t)$, $d\eta_D/\eta_D$ — and full-scale variables. The full-scale variables include the relative differences $d\rho^{sea}/\rho^{sea}$, $d\nu^{sea}/\nu^{sea}$, dD^S/D^S, dL^S/L^S and dS^S/S^S (which may be determined independently and thus may be presumed known for the purpose of this uncertainty analysis), the difference dC_A (which may also be regarded as a given input for this analysis), and the five terms dV^S/V^S, dn^S/n^S, dT^S/T^S, dQ^S/Q^S, $dSHP^S/SHP^S$. Thus, four of these five terms may be determined from any one of them. Specifically, the four relations (25), which define the relative differences dn^S/n^S, dT^S/T^S, dQ^S/Q^S and $dSHP^S/SHP^S$ in terms of dV^S/V^S, can be expressed in four alternative forms which define the full-scale prediction uncertainties in terms of dn^S/n^S, dT^S/T^S, dQ^S/Q^S or $dSHP^S/SHP^S$. These four alternative forms are considered in [2] for the similar uncertainty analysis of full-scale submarine propulsion predictions using tow-tank model tests. Only the most useful alternative form of the relations (25), which defines the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S and dQ^S/Q^S in terms of $dSHP^S/SHP^S$, is considered here.

This alternative form of the relations (25) is

$$(3-\Gamma+\sigma^\eta)\,D_V = D_P - (\Gamma-\sigma^\eta)\,D_C^{L\nu} - D_\rho^S + D_\eta \tag{26a}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)\,D_N = {}& (1+\sigma^J)(D_P - D_\rho^S + D_\eta) - (\Gamma-\sigma^\eta+3\sigma^J)\,D_C^{L\nu} \\ & -(3-\Gamma+\sigma^\eta)\,D_J^D\end{aligned} \tag{26b}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)\,D_T = {}& (2-\Gamma+\sigma^t)(D_P + D_\eta) + (\Gamma+2\sigma^\eta-3\sigma^t)\,D_C^{L\nu} \\ & +(1+\sigma^\eta-\sigma^t)\,D_\rho^S - (3-\Gamma+\sigma^\eta)\,D_t\end{aligned} \tag{26c}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)\,D_Q = {}& (2-\Gamma+\sigma^\eta-\sigma^J)\,D_P + (\Gamma-\sigma^\eta+3\sigma^J)\,D_C^{L\nu} \\ & +(1+\sigma^J)(D_\rho^S - D_\eta) + (3-\Gamma+\sigma^\eta)\,D_J^D\end{aligned} \tag{26d}$$

As was already noted, the foregoing relations define the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S and dQ^S/Q^S in terms of $dSHP^S/SHP^S$.

Expressions (9) and (11) show that the relative difference

$$D_E = \frac{dEHP^S}{EHP^S} \tag{27}$$

can be obtained from the foregoing expressions for the relative difference $D_P = dSHP^S/SHP^S$. Specifically, expression (25d) yields

$$D_E = (3-\Gamma)\,D_V + \Gamma\, D_C^{L\nu} + D_\rho^S \tag{28a}$$

The relations $EHP^S = \eta_D\, SHP^S$, (22) and (26a) yield

$$(3-\Gamma+\sigma^\eta)\,D_E = (3-\Gamma)(D_P + D_\eta) + \sigma^\eta\,(3D_C^{L\nu} + D_\rho^S) \tag{28b}$$

The relative uncertainties $\delta V^S/V^S$, $\delta n^S/n^S$, $\delta T^S/T^S$, $\delta Q^S/Q^S$ and $\delta SHP^S/SHP^S$ corresponding to the relative differences dV^S/V^S, dn^S/n^S, dT^S/T^S, dQ^S/Q^S and $dSHP^S/SHP^S$ defined in the foregoing alternative relations are readily determined by taking the square root of the sum of the square of every term in these relations. Thus, we define the notation

$$U_C^{L\nu} = \frac{(\delta C_R)^2 + (\delta C_A)^2}{10\,(C_F^S)^3} + \left(\frac{\delta L^S}{L^S}\right)^2 + \left(\frac{\delta \nu^{sea}}{\nu^{sea}}\right)^2 \qquad U_\rho^S = \left(\frac{\delta \rho^{sea}}{\rho^{sea}}\right)^2 + \left(\frac{\delta S^S}{S^S}\right)^2 \tag{29a}$$

$$U_V = \left(\frac{\delta V^S}{V^S}\right)^2 \qquad U_N = \left(\frac{\delta n^S}{n^S}\right)^2 \qquad U_T = \left(\frac{\delta T^S}{T^S}\right)^2 \qquad U_Q = \left(\frac{\delta Q^S}{Q^S}\right)^2 \tag{29b}$$

$$U_P = \left(\frac{\delta SHP^S}{SHP^S}\right)^2 \qquad U_E = \left(\frac{\delta EHP^S}{EHP^S}\right)^2 \qquad U_t = \left(\frac{\delta(1-t)}{1-t}\right)^2 \tag{29c}$$

$$U_\eta = \left(\frac{\delta \eta_D}{\eta_D}\right)^2 \qquad U_J^D = \left(\frac{\delta J_V}{J_V}\right)^2 + \left(\frac{\delta D^S}{D^S}\right)^2 \tag{29d}$$

corresponding to (21) and (24). We also define the relative uncertainties attached to the full-scale measurements of V^S, n^S, T^S, Q^S, SHP^S and EHP^S, i.e.

$$U_V^{fsm} = \left(\frac{\delta V_{fsm}^S}{V^S}\right)^2 \qquad U_N^{fsm} = \left(\frac{\delta n_{fsm}^S}{n^S}\right)^2 \qquad U_T^{fsm} = \left(\frac{\delta T_{fsm}^S}{T^S}\right)^2 \tag{29e}$$

$$U_Q^{fsm} = \left(\frac{\delta Q_{fsm}^S}{Q^S}\right)^2 \qquad U_P^{fsm} = \left(\frac{\delta SHP_{fsm}^S}{SHP^S}\right)^2 \qquad U_E^{fsm} = \left(\frac{\delta EHP_{fsm}^S}{EHP^S}\right)^2 \tag{29f}$$

where the subscript or superscript *fsm* means *full-scale measurement.* The uncertainty U_E^{fsm} attached to the effective horsepower EHP^S of the ship is not defined in practice because measurements of EHP_{fsm}^S are not available. Thus, the term EHP_{fsm}^S may be ignored in the expressions given below.

Expressions (25) and (28a) yield

$$U_N = (1+\sigma^J)^2 U_V^{fsm} + (\sigma^J)^2 U_C^{L\nu} + U_J^D + U_N^{fsm} \tag{30a}$$

$$U_T = (2-\Gamma+\sigma^t)^2 U_V^{fsm} + (\Gamma-\sigma^t)^2 U_C^{L\nu} + U_\rho^S + U_t + U_T^{fsm} \tag{30b}$$

$$U_Q = (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_V^{fsm} + (\Gamma-\sigma^\eta+\sigma^J)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_J^D + U_Q^{fsm} \tag{30c}$$

$$U_P = (3-\Gamma+\sigma^\eta)^2 U_V^{fsm} + (\Gamma-\sigma^\eta)^2 U_C^{L\nu} + U_\rho^S + U_\eta + U_P^{fsm} \tag{30d}$$

$$U_E = (3-\Gamma)^2 U_V^{fsm} + \Gamma^2 U_C^{L\nu} + U_\rho^S + U_E^{fsm} \tag{30e}$$

Similarly, (26) and (28b) yield

$$(3-\Gamma+\sigma^\eta)^2 U_V = U_P^{fsm} + (\Gamma-\sigma^\eta)^2 U_C^{L\nu} + U_\rho^S + U_\eta + (3-\Gamma+\sigma^\eta)^2 U_V^{fsm} \tag{31a}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)^2 U_N = {} & (1+\sigma^J)^2 (U_P^{fsm} + U_\rho^S + U_\eta) + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ & + (3-\Gamma+\sigma^\eta)^2 (U_J^D + U_N^{fsm})\end{aligned} \tag{31b}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)^2 U_T = {} & (2-\Gamma+\sigma^t)^2 (U_P^{fsm} + U_\eta) + (\Gamma+2\sigma^\eta-3\sigma^t)^2 U_C^{L\nu} \\ & + (1+\sigma^\eta-\sigma^t)^2 U_\rho^S + (3-\Gamma+\sigma^\eta)^2 (U_t + U_T^{fsm})\end{aligned} \tag{31c}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)^2 U_Q = {} & (2-\Gamma+\sigma^\eta-\sigma^J)^2 U_P^{fsm} + (\Gamma-\sigma^\eta+3\sigma^J)^2 U_C^{L\nu} \\ & + (1+\sigma^J)^2 (U_\rho^S + U_\eta) + (3-\Gamma+\sigma^\eta)^2 (U_J^D + U_Q^{fsm})\end{aligned} \tag{31d}$$

$$\begin{aligned}(3-\Gamma+\sigma^\eta)^2 U_E = {} & (3-\Gamma)^2 (U_P^{fsm} + U_\eta) + (\sigma^\eta)^2 (9 U_C^{L\nu} + U_\rho^S) \\ & + (3-\Gamma+\sigma^\eta)^2 U_E^{fsm}\end{aligned} \tag{31e}$$

The two sets of alternative expressions (30) and (31), and expressions (29), (23) and (20), define the uncertainties attached to the full-scale predictions of the ship speed V^S, the propeller rpm N^S, thrust T^S and torque Q^S, the shaft horsepower SHP^S and the effective horsepower EHP^S for the two cases in which V^S or SHP^S are held constant (within the accuracy of full-scale measurements).

APPENDIX C:

FORTRAN-CODE & INPUT-OUTPUT FILES

The source file LCCUA.f of the program LCCUA , which represents the Fortran implementation of the uncertainty analysis expounded in Appendix B , is given in Appendix C. The symbols defined in the analysis and used in the Fortran-code LCCUA are fairly consistent.

An example of the input file LCCUA.in required by LCCUA.f , and of the corresponding output file LCCUA.out generated by LCCUA.f , is also given in this Appendix. The attached example input file LCCUA.in and output file LCCUA.out corresponds to the previously-defined case MFC , in which the uncertainties attached to model-scale and full-scale variables and to the value of the correlation coefficient are included.

FORTRAN CODE

```
c
c     Global uncertainty analysis of full-scale submarine
c     propulsion predictions using model tests in LCC
c     Francis Noblesse (April 98)
c
      program LCCUA
c
      character LCCxp*50 , date*50 , model*50 , prop*50 ,
   &  EHPxp*50 , SHPxp*50 , comment*80
c
      real ro , nu , Uro , Unu , L , S , D , UL , US , UD ,
   &  CR , UCR , Vknot , RT , DelR , nrpm , T , Qinlb ,
   &  UV , URT , UDelR , Un , UT , UQ , JVCT , tdCT , etaCT ,
   &  nusea , Uros , Unus , LS , VSknot , ULS , USS , UDS ,
   &  UVfsm , UNfsm , UTfsm , UQfsm , UPfsm , CA , dCA ,
   &  V , VS , n , Q , CTCR , CFCR , Ri , CT , CF ,
   &  JV , td , eta , Uro2 , Unu2 , UL2 , US2 , UD2 ,
   &  UV2 , URi , URi2 , Un2 , UT2 , UQ2 , UCA ,
   &  UCTCR2 , UCTCR , UCFCR2 , UCFCR ,
   &  UCT2 , UCT , UCF2 , UCF ,
   &  UJV2 , Utd2 , Ueta2, UJV , Utd , Ueta ,
   &  CFS , CTS , UroS2 , UJD2 , cofCFS , UCLnu2 ,
   &  Gamma , sigmaJ , sigmat , sigmeta ,
   &  UVfsm2 , UNfsm2 , UTfsm2 , UQfsm2 , UPfsm2 ,
   &  UN2V , UT2V , UQ2V , UP2V , UE2V ,
   &  UVV , UNV , UTV , UQV , UPV , UEV , UAV ,
   &  UV2P , UN2P , UT2P , UQ2P , UE2P ,
   &  UPP , UVP , UNP , UTP , UQP , UEP , UAP
c
c     READ INPUT VARIABLES
c
      open(11,file='LCCUA.in',status='old')
c
      read(11,*) LCCxp
      read(11,*) date
      read(11,*) model
      read(11,*) prop
      read(11,*) EHPxp
      read(11,*) SHPxp
      read(11,*) comment
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*)
```

```
read(11,*)
read(11,*) ro , nu
read(11,*)
read(11,*)
read(11,*)
read(11,*) Uro, Unu
read(11,*)
read(11,*)
read(11,*)
read(11,*) L , S , D
read(11,*)
read(11,*)
read(11,*)
read(11,*) UL , US , UD
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) CR
read(11,*)
read(11,*)
read(11,*) UCR
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) Vknot , RT , DelR
read(11,*)
read(11,*)
read(11,*) nrpm , T , Qinlb
read(11,*)
read(11,*)
read(11,*)
read(11,*) UV , URT , UDelR , Un , UT , UQ
read(11,*)
read(11,*)
read(11,*)
read(11,*) JVCT , tdCT , etaCT
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*)
read(11,*) nusea
read(11,*)
read(11,*)
```

```
      read(11,*)
      read(11,*) Uros , Unus
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) LS , VSknot
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) ULS , USS , UDS
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) UVfsm , UNfsm , UTfsm , UQfsm , UPfsm
      read(11,*)
      read(11,*)
      read(11,*)
      read(11,*) CA , dCA
c
      close(11,status='keep')
c
c     About notation :
c     U stands for relative Uncertainty
c     fsm stands for Full-Scale Measurement uncertainty
c
c     PRELIMINARY  TRANSFORMATIONS
c
c     Rescale nu and nusea
c
      nu = nu / 100000.
      nusea = nusea / 100000.
c
c     Transform speeds from knots to ft/sec
c
      V = 1.6878 * Vknot
      VS = 1.6878 * VSknot
c
c     Transform rpm into rps
c
      n = nrpm / 60.
c
c     Transform torque from in-lb to ft-lb
c
      Q = Qinlb / 12.
c
c     Transform input percent uncertainties
```

```
c
        Uro = 0.01 * Uro
        Unu = 0.01 * Unu
c
        UL = 0.01 * UL
        US = 0.01 * US
        UD = 0.01 * UD
c
        UCR = 0.01 * UCR
c
        UV = 0.01 * UV
        URT = 0.01 * URT
        UDelR = 0.01 * UDelR
c
        Un = 0.01 * Un
        UT = 0.01 * UT
        UQ = 0.01 * UQ
c
        Uros = 0.01 * Uros
        Unus = 0.01 * Unus
c
        ULS = 0.01 * ULS
        USS = 0.01 * USS
        UDS = 0.01 * UDS
c
        UVfsm = 0.01 * UVfsm
        UNfsm = 0.01 * UNfsm
        UTfsm = 0.01 * UTfsm
        UQfsm = 0.01 * UQfsm
        UPfsm = 0.01 * UPfsm
c
c       MODEL-SCALE VARIABLES
c
c       Compute Ri , CT & CF
c
        Ri = RT - DelR
        CT = 2. * Ri / ( ro * S * V * V )
        CF = 0.075 / ( LOG10( V * L / nu ) - 2. )**2
c
c       Compute JV , td=1-t & eta=etaD
c
        JV = V / ( n * D )
        td = Ri / T
        eta = V * Ri / ( 6.2831853 * n * Q )
c
c       PRELIMINARY CALCULATIONS FOR MODEL-SCALE UNCERTAINTIES
```

```
c
      Uro2 = Uro * Uro
      Unu2 = Unu * Unu
c
      UL2 = UL * UL
      US2 = US * US
      UD2 = UD * UD
c
      UV2 = UV * UV
c
      URi = ( URT * RT )**2 + ( UDelR * DelR )**2
      URi = SQRT( URi ) / Ri
      URi2 = URi * URi
c
      Un2 = Un * Un
      UT2 = UT * UT
      UQ2 = UQ * UQ
c
c     MODEL-SCALE UNCERTAINTIES
c
c     Compute dCT / CT
c
      UCT2 = URi2 + Uro2 + US2 + 4. * UV2
      UCT = 100. * SQRT( UCT2 )
c
c     Compute dCF / CF
c
      UCF2 = 10. * CF * ( UV2 + UL2 + Unu2 )
      UCF = 100. * SQRT( UCF2 )
c
c     Compute dJV / JV , dtd / td & deta / eta
c
      UJV2 = UV2 + Un2 + UD2
      Utd2 = URi2 + UT2
      Ueta2 = UV2 +  URi2 + Un2 + UQ2
c
      UJV = 100. * SQRT( UJV2 )
      Utd = 100. * SQRT( Utd2 )
      Ueta = 100. * SQRT( Ueta2 )
c
c     PRELIMINARY CALCULATIONS FOR FULL-SCALE UNCERTAINTIES
c
c     Compute CFS & CTS
c
      CFS = 0.075 / ( LOG10( VS * LS / nusea ) - 2. )**2
      CTS = CFS + CR + CA
```

```
c
c     Compute (drhosea/rhosea)^2+(dSS/SS)^2 & (dJV/JV)^2+(dDS/DS)^2
c
      UroS2 = Uros**2 + USS**2
      UJD2 = UJV2 + UDS**2
c
c     Compute UCLnu2 & Gamma
c
      cofCFS = 10. * CFS**3
c
      UCLnu2 = ( CR * UCR )**2 + dCA**2
      UCLnu2 = UCLnu2 / cofCFS + ULS**2 + Unus**2
c
      cofCFS = SQRT( cofCFS )
      Gamma = cofCFS / CTS
c
c     Compute sigmaJ , sigmat & sigmeta
c
      sigmaJ = cofCFS * JVCT / JV
      sigmat = cofCFS * tdCT / td
      sigmeta = cofCFS * etaCT / eta
c
c     Compute squares of full-scale measurement uncertainties
c
      UVfsm2 = UVfsm * UVfsm
      UNfsm2 = UNfsm * UNfsm
      UTfsm2 = UTfsm * UTfsm
      UQfsm2 = UQfsm * UQfsm
      UPfsm2 = UPfsm * UPfsm
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN SPEED
c
      UN2V = UVfsm2 * ( 1. + sigmaJ )**2 + UCLnu2 * sigmaJ**2
      UN2V = UN2V + UJD2 + UNfsm2
c
      UT2V = UVfsm2 * ( 2. - Gamma + sigmat )**2
      UT2V = UT2V + UCLnu2 * ( Gamma - sigmat )**2
      UT2V = UT2V + UroS2 + Utd2 + UTfsm2
c
      UQ2V = UVfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
      UQ2V = UQ2V + UCLnu2 * ( Gamma - sigmeta + sigmaJ )**2
      UQ2V = UQ2V + UroS2 + Ueta2 + UJD2 + UQfsm2
c
      UP2V = UVfsm2 * ( 3. - Gamma + sigmeta )**2
      UP2V = UP2V + UCLnu2 * ( Gamma - sigmeta )**2
      UP2V = UP2V + UroS2 + Ueta2 + UPfsm2
```

```
c
      UE2V = UVfsm2 * ( 3. - Gamma )**2 + UCLnu2 * Gamma**2 + UroS2
c
      UVV = 100. * UVfsm
      UNV = 100. * SQRT( UN2V )
      UTV = 100. * SQRT( UT2V )
      UQV = 100. * SQRT( UQ2V )
      UPV = 100. * SQRT( UP2V )
      UEV = 100. * SQRT( UE2V )
      UAV = 20. * SQRT( UVfsm2 + UN2V + UT2V + UQ2V + UP2V )
c
c     FULL-SCALE UNCERTAINTIES @ a GIVEN SHAFT HORSEPOWER
c
      UV2P = UPfsm2 + UCLnu2 * (Gamma-sigmeta)**2 + UroS2 + Ueta2
      UV2P = UV2P / ( 3. - Gamma + sigmeta )**2 + UVfsm2
c
      UN2P = ( UPfsm2 + UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
      UN2P = UN2P + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UN2P = UN2P / ( 3. - Gamma + sigmeta )**2 + UJD2 + UNfsm2
c
      UT2P = ( UPfsm2 + Ueta2 ) * ( 2. - Gamma + sigmat )**2
      UT2P = UT2P + UCLnu2 * (Gamma+2.*sigmeta-3.*sigmat)**2
      UT2P = UT2P + UroS2 * ( 1. + sigmeta - sigmat )**2
      UT2P = UT2P / ( 3. - Gamma + sigmeta )**2 + Utd2 + UTfsm2
c
      UQ2P = UPfsm2 * ( 2. - Gamma + sigmeta - sigmaJ )**2
      UQ2P = UQ2P + UCLnu2 * ( Gamma - sigmeta + 3. * sigmaJ )**2
      UQ2P = UQ2P + ( UroS2 + Ueta2 ) * ( 1. + sigmaJ )**2
      UQ2P = UQ2P / ( 3. - Gamma + sigmeta )**2 + UJD2 + UQfsm2
c
      UE2P = ( UPfsm2 + Ueta2 ) * ( 3. - Gamma )**2
      UE2P = UE2P + ( 9. * UCLnu2 + UroS2 ) * sigmeta**2
      UE2P = UE2P / ( 3. - Gamma + sigmeta )**2
c
      UPP = 100. * UPfsm
      UVP = 100. * SQRT( UV2P )
      UNP = 100. * SQRT( UN2P )
      UTP = 100. * SQRT( UT2P )
      UQP = 100. * SQRT( UQ2P )
      UEP = 100. * SQRT( UE2P )
      UAP = 20. * SQRT( UV2P + UN2P + UT2P + UQ2P + UPfsm2 )
c
c     WRITE INPUT VARIABLES & OUTPUT RESULTS
c
c     Express relative uncertainties in percent
c
```

```
      Uro = 100. * Uro
      Unu = 100. * Unu
c
      UL = 100. * UL
      US = 100. * US
      UD = 100. * UD
c
      UCR = 100. * UCR
c
      UV = 100. * UV
      URT = 100. * URT
      UDelR = 100. * UDelR
c
      Un = 100. * Un
      UT = 100. * UT
      UQ = 100. * UQ
c
      Uros = 100. * Uros
      Unus = 100. * Unus
c
      ULS = 100. * ULS
      USS = 100. * USS
      UDS = 100. * UDS
c
      UVfsm = 100. * UVfsm
      UNfsm = 100. * UNfsm
      UTfsm = 100. * UTfsm
      UQfsm = 100. * UQfsm
      UPfsm = 100. * UPfsm
c
      UCA = 100. * dCA / CA
c
      open(12,file='LCCUA.out',status='new')
c
      write(12,*) LCCxp
      write(12,*) date
      write(12,*) model
      write(12,*) prop
      write(12,*) EHPxp
      write(12,*) SHPxp
      write(12,*) comment
c
      write(12,*)
      write(12,*) ' INPUT VARIABLES'
      write(12,*)
c
```

```
      write(12,*)
      write(12,*) ' TANK-WATER PROPERTIES'
      write(12,*)
      write(12,101) ro
      write(12,102) nu
      write(12,103) Uro
      write(12,104) Unu
c
      write(12,*)
      write(12,*) ' MODEL GEOMETRY'
      write(12,*)
      write(12,105) L
      write(12,106) S
      write(12,107) D
      write(12,108) UL
      write(12,109) US
      write(12,110) UD
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : RESISTANCE TESTS'
      write(12,*)
      write(12,111) CR
      write(12,112) UCR
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES : PROPULSION TESTS'
      write(12,*)
      write(12,114) Vknot
      write(12,115) RT
      write(12,116) DelR
      write(12,117) nrpm
      write(12,118) T
      write(12,119) Qinlb
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS'
      write(12,*)
      write(12,120) UV
      write(12,121) URT
      write(12,122) UDelR
      write(12,123) Un
      write(12,124) UT
      write(12,125) UQ
c
      write(12,*)
      write(12,*) ' OTHER MODEL-SCALE VARIABLES'
```

```
      write(12,*)
      write(12,126) JVCT
      write(12,127) tdCT
      write(12,128) etaCT
c
      write(12,*)
      write(12,*) ' SEA-WATER PROPERTIES'
      write(12,*)
      write(12,151) nusea
      write(12,152) Uros
      write(12,153) Unus
c
      write(12,*)
      write(12,*) ' FULL-SCALE SHIP'
      write(12,*)
      write(12,154) LS
      write(12,155) VSknot
      write(12,156) ULS
      write(12,157) USS
      write(12,158) UDS
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF FULL-SCALE MEASUREMENTS'
      write(12,*)
      write(12,159) UVfsm
      write(12,160) UNfsm
      write(12,161) UTfsm
      write(12,162) UQfsm
      write(12,163) UPfsm
c
      write(12,*)
      write(12,*) ' SCALING ALLOWANCE'
      write(12,*)
      write(12,171) CA
      write(12,172) dCA
c
      write(12,*)
      write(12,*)
      write(12,*) ' OUTPUT VARIABLES'
      write(12,*)
c
      write(12,*)
      write(12,*) ' MODEL-SCALE VARIABLES'
      write(12,*)
      write(12,204) CT
      write(12,205) CF
```

```
      write(12,206) CR
      write(12,*)
      write(12,207) JV
      write(12,208) td
      write(12,209) eta
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES OF MODEL-SCALE VARIABLES'
      write(12,*)
      write(12,213) UCT
      write(12,214) UCF
      write(12,215) UCR
      write(12,216) UCA
      write(12,*)
      write(12,217) UJV
      write(12,218) Utd
      write(12,219) Ueta
c
      write(12,*)
      write(12,*) ' FULL-SCALE VARIABLES'
      write(12,*)
      write(12,220) CTS
      write(12,221) CFS
      write(12,222) CR
      write(12,223) CA
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      SPEED'
      write(12,*)
      write(12,311) UVV
      write(12,312) UNV
      write(12,313) UTV
      write(12,314) UQV
      write(12,315) UPV
      write(12,316) UEV
      write(12,317) UAV
c
      write(12,*)
      write(12,*) ' UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN
      SHP'
      write(12,*)
      write(12,321) UVP
      write(12,322) UNP
      write(12,323) UTP
      write(12,324) UQP
```

```
      write(12,325) UPP
      write(12,326) UEP
      write(12,327) UAP
c
      close(12,status='keep')
c
c     FORMATS
c
101   format(' water density (slug/ft**3) :              ',F11.3)
102   format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
103   format(' percent uncertainty of density :  ',F8.2)
104   format(' percent uncertainty of viscosity : ',F8.2)
c
105   format(' length of model (ft) :        ',F8.3)
106   format(' wetted area (ft**2) :         ',F8.3)
107   format(' diameter of propeller (ft) :  ',F8.4)
108   format(' percent uncertainty of length :        ',F8.2)
109   format(' percent uncertainty of wetted surface : ',F8.2)
110   format(' percent uncertainty of prop diameter :  ',F8.2)
c
111   format(' residuary-resistance coefficient :               ',F10.5)
112   format(' percent uncertainty of residuary-resistance coef :  ',F8.2)
c
114   format(' reference velocity (knots) :  ',F8.2)
115   format(' drag RT (lbs) :             ',F8.2)
116   format(' drag DeltaR (lbs) :         ',F8.2)
117   format(' propeller rpm :             ',F8.2)
118   format(' propeller thrust (lbs) :     ',F8.2)
119   format(' propeller torque (in-lbs) :  ',F8.2)
c
120   format(' percent uncertainty of reference velocity (knots) :  ',F8.2)
121   format(' percent uncertainty of drag RT (lbs) :              ',F8.2)
122   format(' percent uncertainty of drag DeltaR (lbs) :          ',F8.2)
123   format(' percent uncertainty of propeller rpm :              ',F8.2)
124   format(' percent uncertainty of prop thrust (lbs) :          ',F8.2)
125   format(' percent uncertainty of prop torque (in-lbs) :       ',F8.2)
c
126   format(' slope d JV / d CT :  ',F9.3)
127   format(' slope d (1-t) / d CT : ',F9.3)
128   format(' slope d etaD /  d CT : ',F9.3)
c
151   format(' kinematic viscosity coefficient (ft**2/sec) : ',E11.4)
152   format(' percent uncertainty of density :  ',F8.2)
153   format(' percent uncertainty of viscosity : ',F8.2)
c
154   format(' ship length (ft) :             ',F8.2)
```

```
155   format(' ship speed (knots) :        ',F11.1)
c
156   format(' percent uncertainty of ship length :    ',F8.2)
157   format(' percent uncertainty of wetted surface : ',F8.2)
158   format(' percent uncertainty of prop diameter :  ',F8.2)
c
159   format(' percent uncertainty of ship speed :   ',F8.2)
160   format(' percent uncertainty of prop rpm :     ',F8.2)
161   format(' percent uncertainty of prop thrust :  ',F8.2)
162   format(' percent uncertainty of prop torque :  ',F8.2)
163   format(' percent uncertainty of SHP :          ',F8.2)
c
171   format(' correlation allowance :       ',F11.5)
172   format(' uncertainty of allowance :  ',F11.5)
c
201   format(' total resistance coefficient CT :         ',F10.5)
202   format(' friction resistance coefficient CF :      ',F10.5)
203   format(' residuary resistance coefficient CR :    ',F10.5)
c
204   format(' total resistance coefficient CT :         ',F10.5)
205   format(' friction resistance coefficient CF :      ',F10.5)
206   format(' residuary resistance coefficient CR :    ',F10.5)
c
207   format(' advance ratio JV :            ',F8.2)
208   format(' thrust-deduction factor 1-t : ',F8.2)
209   format(' propulsive efficiency etaD :  ',F8.2)
c
210   format(' percent uncertainty of CT : ',F8.2)
211   format(' percent uncertainty of CF : ',F8.2)
212   format(' percent uncertainty of CR : ',F8.2)
c
213   format(' percent uncertainty of CT : ',F8.2)
214   format(' percent uncertainty of CF : ',F8.2)
215   format(' percent uncertainty of CR : ',F8.2)
216   format(' percent uncertainty of CA : ',F8.2)
c
217   format(' percent uncertainty of JV :   ',F8.2)
218   format(' percent uncertainty of 1-t :  ',F8.2)
219   format(' percent uncertainty of etaD : ',F8.2)
c
220   format(' total resistance coefficient CT :        ',F10.5)
221   format(' friction resistance coefficient CF :    ',F10.5)
222   format(' residuary resistance coefficient CR :  ',F10.5)
223   format(' correlation allowance coefficient CA : ',F10.5)
c
311   format(' percent uncertainty of ship speed :   ',F8.2)
```

```
312   format(' percent uncertainty of prop rpm :    ',F8.2)
313   format(' percent uncertainty of prop thrust : ',F8.2)
314   format(' percent uncertainty of prop torque : ',F8.2)
315   format(' percent uncertainty of SHP :         ',F8.2)
316   format(' percent uncertainty of EHP :         ',F8.2)
317   format(' percent overall uncertainty :        ',F8.2)
c
321   format(' percent uncertainty of ship speed :  ',F8.2)
322   format(' percent uncertainty of prop rpm :    ',F8.2)
323   format(' percent uncertainty of prop thrust : ',F8.2)
324   format(' percent uncertainty of prop torque : ',F8.2)
325   format(' percent uncertainty of SHP :         ',F8.2)
326   format(' percent uncertainty of EHP :         ',F8.2)
327   format(' percent overall uncertainty :        ',F8.2)
c
      stop
      end
```

EXAMPLE INPUT FILE

' LCC EXP '
' DATE: XXXX'
' MODEL No. XXXX'
' PROPELLER No. XXXX'
' EHP EXPERIMENT No. XXX '
' SHP EXPERIMENT No. XXX '
' COMMENTS: CASE MFC '

MODEL-SCALE VARIABLES AND UNCERTAINTIES

Tank-water density (rho) and kinematic viscosity (nu)
rho (slug/ft**3)   nu X 10**5 (ft**2/sec)
1.9367 ,   1.084

Percent relative uncertainties of rho & nu
density   kinematic viscosity
0.14 ,   2.1

Model geometry
length (ft)   area (ft**2)   prop diameter (ft)
22.697 ,   138.179 ,   0.9986

Percent relative uncertainties of model geometry
length   area   prop diameter
0.14 ,   0.71 ,   0.07

RESISTANCE (EHP) TESTS

Residuary-resistance coefficient
0.00065

Percent relative uncertainty of residuary-resistance coefficient
12.0

PROPULSION TESTS

ref. velocity (knots)   RT (lbs)   DeltaR
23.7 ,   717.89 ,   191.1

rpm   thrust (lbs)   torque (in-lbs)
1175.0 , 878.0 ,   2585.0

Percent relative uncertainties

ref. vel.	RT	DeltaR	rpm	thrust	torque
1.4 ,	2.1 ,	2.1 ,	0.28 ,	0.71 ,	0.42

Other model variables : slopes of 1-t , JV & etaD versus CT

dJV/dCT	d(1-t)/dCT	detaD/dCT
-0.249 ,	0.067 ,	-0.015

FULL-SCALE VARIABLES AND UNCERTAINTIES

Sea-water kinematic viscosity
nu X 10**5 (ft**2/sec)
1.282

Percent relative uncertainties of sea-water properties

density	kinematic viscosity
1.0 ,	2.0

Full-scale variables

ship length (ft)	ship speed (knots)
380.0 ,	25.0

Percent relative uncertainties of full-scale geometry

length	area	prop diameter
0.5 ,	1.0 ,	0.1

Percent relative uncertainties of full-scale measurements

speed	rpm	thrust	torque	SHP
0.6 ,	0.4 ,	3.0 ,	0.9 ,	0.9

SCALING ALLOWANCE

CA	dCA
0.00035 ,	0.0001

EXAMPLE OUTPUT FILE

LCC EXP
DATE: XXXX
MODEL No. XXXX
PROPELLER No. XXXX
EHP EXPERIMENT No. XXX
SHP EXPERIMENT No. XXX
COMMENTS: CASE MFC

INPUT VARIABLES

TANK-WATER PROPERTIES

water density (slug/ft**3) : 1.937
kinematic viscosity coefficient (ft**2/sec) : 0.1084E-04
percent uncertainty of density : 0.14
percent uncertainty of viscosity : 2.10

MODEL GEOMETRY

length of model (ft) : 22.697
wetted area (ft**2) : 138.179
diameter of propeller (ft) : 0.9986
percent uncertainty of length : 0.14
percent uncertainty of wetted surface : 0.71
percent uncertainty of prop diameter : 0.07

MODEL-SCALE VARIABLES : RESISTANCE TESTS

residuary-resistance coefficient : 0.00065
percent uncertainty of residuary-resistance coef : 12.00

MODEL-SCALE VARIABLES : PROPULSION TESTS

reference velocity (knots) : 23.70
drag RT (lbs) : 717.89
drag DeltaR (lbs) : 191.10
propeller rpm : 1175.00
propeller thrust (lbs) : 878.00
propeller torque (in-lbs) : 2585.00

UNCERTAINTIES OF MODEL-SCALE MEASUREMENTS

percent uncertainty of reference velocity (knots) : 1.40

percent uncertainty of drag RT (lbs) : 2.10
percent uncertainty of drag DeltaR (lbs) : 2.10
percent uncertainty of propeller rpm : 0.28
percent uncertainty of prop thrust (lbs) : 0.71
percent uncertainty of prop torque (in-lbs) : 0.42

OTHER MODEL-SCALE VARIABLES

slope d JV / d CT : -0.249
slope d (1-t) / d CT : 0.067
slope d etaD / d CT : -0.015

SEA-WATER PROPERTIES

kinematic viscosity coefficient (ft**2/sec) : 0.1282E-04
percent uncertainty of density : 1.00
percent uncertainty of viscosity : 2.00

FULL-SCALE SHIP

ship length (ft) : 380.00
ship speed (knots) : 25.0
percent uncertainty of ship length : 0.50
percent uncertainty of wetted surface : 1.00
percent uncertainty of prop diameter : 0.10

UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

percent uncertainty of ship speed : 0.60
percent uncertainty of prop rpm : 0.40
percent uncertainty of prop thrust : 3.00
percent uncertainty of prop torque : 0.90
percent uncertainty of SHP : 0.90

SCALING ALLOWANCE

correlation allowance : 0.00035
uncertainty of allowance : 0.00010

OUTPUT VARIABLES

MODEL-SCALE VARIABLES

total resistance coefficient CT : 0.00246
friction resistance coefficient CF : 0.00214
residuary resistance coefficient CR : 0.00065

advance ratio JV : 2.05
thrust-deduction factor 1-t : 0.60
propulsive efficiency etaD : 0.79

UNCERTAINTIES OF MODEL-SCALE VARIABLES

percent uncertainty of CT : 4.14
percent uncertainty of CF : 0.37
percent uncertainty of CR : 12.00
percent uncertainty of CA : 28.57

percent uncertainty of JV : 1.43
percent uncertainty of 1-t : 3.05
percent uncertainty of etaD : 3.31

FULL-SCALE VARIABLES

total resistance coefficient CT : 0.00249
friction resistance coefficient CF : 0.00149
residuary resistance coefficient CR : 0.00065
correlation allowance coefficient CA : 0.00035

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SPEED

percent uncertainty of ship speed : 0.60
percent uncertainty of prop rpm : 1.60
percent uncertainty of prop thrust : 6.90
percent uncertainty of prop torque : 6.57
percent uncertainty of SHP : 6.55
percent uncertainty of EHP : 5.57
percent overall uncertainty : 2.34

UNCERTAINTIES of FULL-SCALE PREDICTIONS at a GIVEN SHP

percent uncertainty of ship speed : 2.24
percent uncertainty of prop rpm : 2.62
percent uncertainty of prop thrust : 5.16
percent uncertainty of prop torque : 2.79
percent uncertainty of SHP : 0.90
percent uncertainty of EHP : 3.43
percent overall uncertainty : 1.37

APPENDIX D :

REPEATABILITY OF MODEL-SCALE MEASUREMENTS

The precision uncertainties associated with submarine-model large cavitation channel (LCC) testing are investigated by considering two test series. These two test series are representative of the submarine model resistance and powering experimental evaluations performed in the LCC. The test series were performed from June through September 1996. The current model test speed range of 6-30 knots is represented in these tests, as well as the current data collection instrumentation and calibration techniques.

The precision uncertainties of the model measurements of drag, rpm, thrust, and torque are evaluated in two ways. First, the gage calibrations and instrumentation were analyzed for uncertainties. The drag, thrust, and torque gages are calibrated on site and the electronic instrumentation manufacturer specifications are examined. These precision uncertainties are generally very small. A better assessment of the model measurement precision uncertainties is obtained by analyzing the collected test data. This second way of evaluating the measurement precision uncertainties takes into account the whole data collection system, including the effects of changing model conditions during a test series, water flow variations, variation in force gages, instrumentation accuracy, vibrations, and computer collection and recording of the collected model drag, shaft RPM, shaft thrust, and shaft torque values. The methods used to determine the precision uncertainties of the model tests provide conservative uncertainty values for use in the global uncertainty analysis. The precision uncertainties for the measurements of the four main primary model quantities, i.e., model drag, shaft RPM, thrust, and torque, are now examined.

Calibration of the drag, thrust, and torque gages is completed before each test series. The instrumentation currently being used for the model test measurements is presented in Table D.1 .

A typical resistance or powering experiment consists of approximately 20 data spots with each data spot representing the average of 5 seconds of data collected at 400 samples/second for a total sample of 2000 for a set speed, drag, and RPM (for powering) condition.

The precision uncertainty in model drag is calculated by using measured values of drag at the same nominal model speed. A correction is applied to the measured drag to reduce the effects of the speed variation on the measured drag uncertainty. The measured drag is multiplied by $(V_N)^2 / (V_M)^2$, where V_M = measured speed and V_N = nominal speed. EHP tests are used as the source of the data. The precision uncertainties are presented in Tables D.2 and D.3 .

The precision uncertainties for model thrust, torque, and RPM are determined differently from the model drag uncertainty. Typical submarine powering experiments consist in varying the propeller RPM to produce different submarine loadings. The precision uncertainty for the shaft thrust, torque and RPM has been estimated by determining the variation of the thrust, torque, and RPM data from a least-square curve fit through the data spots of a test. Each test contains about 20 data spots which comprise a range of thrust, torque and RPM versus total drag coefficient (C_T) values. The thrust, torque, and RPM are plotted against C_T and a second-order least-square curve is fitted through each set of data. The percent difference between the measured data spot and the curve at each C_T is then determined. Twice the standard error estimate (SEE) divided by an average thrust, torque, or RPM value is taken as the precision uncertainty for that test. The results are presented in Tables D.4 and D.5.

The following table summarizes the precision uncertainties for LCC model measurements of drag, thrust, torque, and RPM

Uncertainties of model-scale measurements used in analysis

drag	thrust	torque	rpm
1.5%	0.5%	0.3%	0.2%

Table D.1. Instrumentation used at the LCC for resistance and powering tests

INSTRUMENT		Used for 1996 tests	Current
RPM	Type	magnetic pick-up to counter	magnetic pick-up to counter
	Manufacturer	Dynapar	Dynapar
	Model		
	Wheel	60-tooth	60-tooth
	Counter	Hewlett Packard	Hewlett Packard
	Counter Model	5316B	5316B
Drag Dynamometer	Manufacturer	NSWCCD	AMTI
	Model	high speed 2000 lb	6-component strut gage
	Type	full bridge strain gauge type	full bridge strain gauge type
	Max longitudnal force	2000 lb	4000 lb
	Max lateral force		2000 lb
	Max pitch moment		25000 ft-lb
	Max roll moment		3000 ft-lb
	Max yaw moment		5000 ft-lb
Thrust and Torque Dynamometer	Manufacturer	Modern Machine & Tool Co., Inc	Modern Machine & Tool Co., Inc
	Model	TQS-3B	TQS-3B
	Type	full bridge strain gauge type	full bridge strain gauge type
	Rated thrust	+/- 3600 lb	+/- 3600 lb
	Rated torque	+/- 15360 in-lb	+/- 15360 in-lb
	Overload T&Q allowed	30%	30%
Signal Conditioner	Manufacturer	Valadyne	Scientific Marine Servies, Inc
	Model	CD19	IAF-01

Table D.2. Model drag measurement uncertainty for the first LCC resistance and powering test series

10 knot, 16.878 ft/s

	RT (lbs)** (data spot)	corrected RT (10 knots)
# of spots	14	14
average	102.539	102.441
2*Stdev	1.289	0.929
%	1.26	**0.91**

18 knot, 30.380 ft/s

	RT (lbs)** (data spot)	corr RT (18 knots)
# of spots	10	10
average	308.413	308.857
2*Stdev	5.109	5.200
%	1.66	**1.68**

23.7 knot, 40.001 ft/s

	RT (lbs)** (data spot)	corr RT (23.7 knots)
# of spots	10	10
average	520.428	521.488
2*Stdev	2.514	2.519
%	0.48	**0.48**

30 knot, 50.634 ft/s

	RT (lbs)** (data spot)	corr RT (30 knots)
# of spots	10	10
average	823.579	824.692
2*Stdev	18.680	18.519
%	2.27	**2.25**

Total Average % **1.33**

** each data spot = an average of 2000 samples collected over a 5 second collection time at a rate of 400 samples/sec.

Table D.3. Model drag measurement uncertainty for the second LCC resistance and powering test series

	10 knot 16.878 ft/s		18 knot 30.380 ft/s	
	RT (lbs)** (data spot)	corrected RT (10 knots)	RT (lbs)** (data spot)	corr RT (18 knots)
# of spots	12	12	12	12
average	131.627	132.370	412.373	413.243
2*Stdev	1.551	1.560	2.196	2.187
%	1.18	**1.18**	0.53	**0.53**

	23.7 knot 40.001 ft/s		30 knot 50.634 ft/s	
	RT (lbs)** (data spot)	corr RT (23.7 knots)	RT (lbs)** (data spot)	corr RT (30 knots)
# of spots	12	12	12	12
average	715.841	717.771	1169.741	1170.641
2*Stdev	2.926	2.658	5.720	4.614
%	0.41	**0.37**	0.49	**0.39**

Total Average % **0.62**

** each data spot = an average of 2000 samples collected over a 5 second collection time at a rate of 400 samples/sec.

Table D.4. Model thrust, torque, and rpm measurement uncertainty for the first LCC test series at model test speed = 23.7 knots

Thrust

23.7 knot data						
exp#	23	27	30	34	41	47
# of spots	48	50	58	58	36	36
2*SEE (%)	0.53	0.47	0.56	0.35	0.33	0.38

Thrust

Results for 23.7 kn tests	
# tests	6
Average (2*SEE)	**0.44 %**

Torque

23.7 knot data						
exp#	23	27	30	34	41	47
# of spots	48	50	58	58	36	36
2*SEE (%)	0.33	0.30	0.34	0.32	0.20	0.27

Torque

Results for 23.7 kn tests	
# tests	6
Average (2*SEE)	**0.29 %**

RPM

23.7 knot data						
exp#	23	27	30	34	41	47
# of spots	48	50	58	58	36	36
2*SEE (%)	0.15	0.14	0.15	0.15	0.12	0.15

RPM

Results for 23.7 kn tests	
# tests	6
Average (2*SEE)	**0.14 %**

Table D.5. Model thrust, torque, and rpm measurement uncertainty for the second LCC test series at model test speed = 23.7 knots

Thrust

23.7 knot data					
exp#	24	28	32	35	37
# of spots	17	24	23	20	20
2*SEE (%)	0.53	0.33	0.26	0.30	0.31

Thrust

Results for 23.7 kn tests	
# tests	5
Average (2*SEE)	**0.35 %**

Torque

23.7 knot data					
exp#	24	28	32	35	37
# of spots	17	24	23	20	20
2*SEE (%)	0.27	0.26	0.24	0.27	0.29

Torque

Results for 23.7 kn tests	
# tests	5
Average (2*SEE)	**0.27 %**

RPM

23.7 knot data					
exp#	24	28	32	35	37
# of spots	17	24	23	20	20
2*SEE (%)	0.13	0.15	0.15	0.14	0.17

RPM

Results for 23.7 kn tests	
# tests	5
Average (2*SEE)	**0.15 %**

The foregoing table defines the precision uncertainties for model-scale measurements of drag, thrust, torque, and RPM in the LCC. The uncertainties in the measurement of the LCC reference flow velocity is now considered. The reference flow velocity for model tests in the LCC is determined by means of LDV measurements of the velocity at a reference point in the flow domain where the pressure coefficient vanishes. The location of this reference point is determined via numerical calculations. Uncertainties in the value of the reference velocity stem primarily from two main sources : the precision errors related to LDV acquisition, and errors associated with the location of the reference point chosen for measuring the reference velocity.

The precision error associated with LDV acquisition is the dominant cause of uncertainty. This error is a measure of the turbulence intensity in the flow, and thus is usually minimal for free-stream flows. The precision error stemming from the repeatability of LDV acquisition at a stationary point is estimated to be 0.2% . However, this error increases when LDV measurements are taken at different locations, and/or adjustments are made to the optics. Blanton [3] shows that the precision error associated with LDV acquisition can be as high as 0.8% .

The secondary contribution to the uncertainties of the LCC reference velocity stems from uncertainties in the location of the reference point, where the reference velocity is measured. It is estimated that an error in the location of the reference point equal to one inch causes a 0.1% error in the reference velocity. The theoretical determination of the reference point is expected to provide an estimate of the location of the reference point with an error approximately equal to 1% of the length of the model. For a typical 20-foot model, the location of the reference point can then be presumed to be known with an error of 2.5 inches. In addition, LDV measurements cannot always be taken exactly at the theoretical reference points due to obstacles and restrictions in optical access. E.g., during the 688 test, measurements were made at 0.85 inch off the theoretical reference point. Obstacles and optical-access difficulties evidently vary from model to model. It is estimated that the distance between the theoretically-determined reference point and the reference

point actually used in the LDV measurements can be as large as 4 inches. The total error in the location of the reference point where the reference velocity is measured can then be as large as 6.5 inches, resulting in an error of 0.65% as was explained previously.

The uncertainty resulting from the 0.8% precision error related to LDV acquisition and the 0.65% error associated with the location of the reference point is given by $(0.8^2 + 0.65^2)^{1/2} = 1.03\%$. Thus, the uncertainty in the value of the reference velocity for LCC model testing is taken equal to 1% in the global uncertainty analysis, as is indicated in the table below.

Uncertainty of LCC reference velocity used in analysis

reference velocity
1%

APPENDIX E:
UNCERTAINTIES OF FULL-SCALE MEASUREMENTS

The relative total (precision + bias) uncertainties of full-scale measurements of the ship speed, the propeller rpm, the thrust, the torque, and the shaft horsepower reported for four full-scale trials (USS Boise SSN764, USS Colombus SSN762, USS Charlotte SSN 766, USS Memphis SSN 691) are given below

Reported uncertainties of full-scale measurements

ship	speed	rpm	thrust	torque	SHP
SSN 764	0.6%	1.9%	4.1%	0.3%	1.9%
SSN 762	0.6%	0.5%	4.1%	0.3%	0.6%
SSN 766	0.3%	0.2%	2.2%	0.9%	0.8%
SSN 691		0.2%	2.2%	1.4%	0.9%

Appreciable variations can be observed in the foregoing uncertainties. Reasonable estimates of these uncertainties are listed below

Uncertainties of full-scale measurements used in analysis

speed	rpm	thrust	torque	SHP
0.6%	0.4%	3.0%	0.9%	0.9%

These estimates of full-scale measurement uncertainties are used in the present uncertainty analysis.

REFERENCES

[1] Hugh W. Coleman and W. Glenn Steele, *Experimentation and uncertainty analysis for engineers,* 1989, John Wiley and Sons.

[2] F. Noblesse, J.R. Lee, M.R. Pfeifer, R.B. Hurwitz, *Global uncertainty analysis of full-scale submarine propulsion predictions using tow-tank model tests,* CD-NSWC Report No. CRDKNSWC/HD-1469-01, Sept 1998.

[3] James N. Blanton and Robert J. Etter, *Laser Doppler Velocimetry on a Body of Revolution in the Large Cavitation Channel,* 1995 ASME Fluids Engineering Division Summer Meeting, Hilton Head, South Carolina.

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